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(54) Ultrasonic imaging system

(57) An ultrasonic imaging system comprises a first array of transducer elements 10 adapted to be coupled to an object to be examined, which elements receive ultrasonic echo signals indicative of acoustic reflecting surfaces in the object. The received echo signals are converted by the first array of elements into electrical signals which are stored at 24 and retrieved so as to provide time reversal (time inversion) and thereafter used to energize a second array of transducer elements 27 coupled to a reconstruction medium 30. The ultrasonic signals transmitted by the second array, responsive to the time-reversed electrical signals, produce in the reconstruction medium a reconstructed acoustic image of the acoustic reflecting surfaces in the object. A visual image of the reconstructed acoustic image is obtained by acousto-optical means 32, such as a Schlieren device, and displayed at 36.

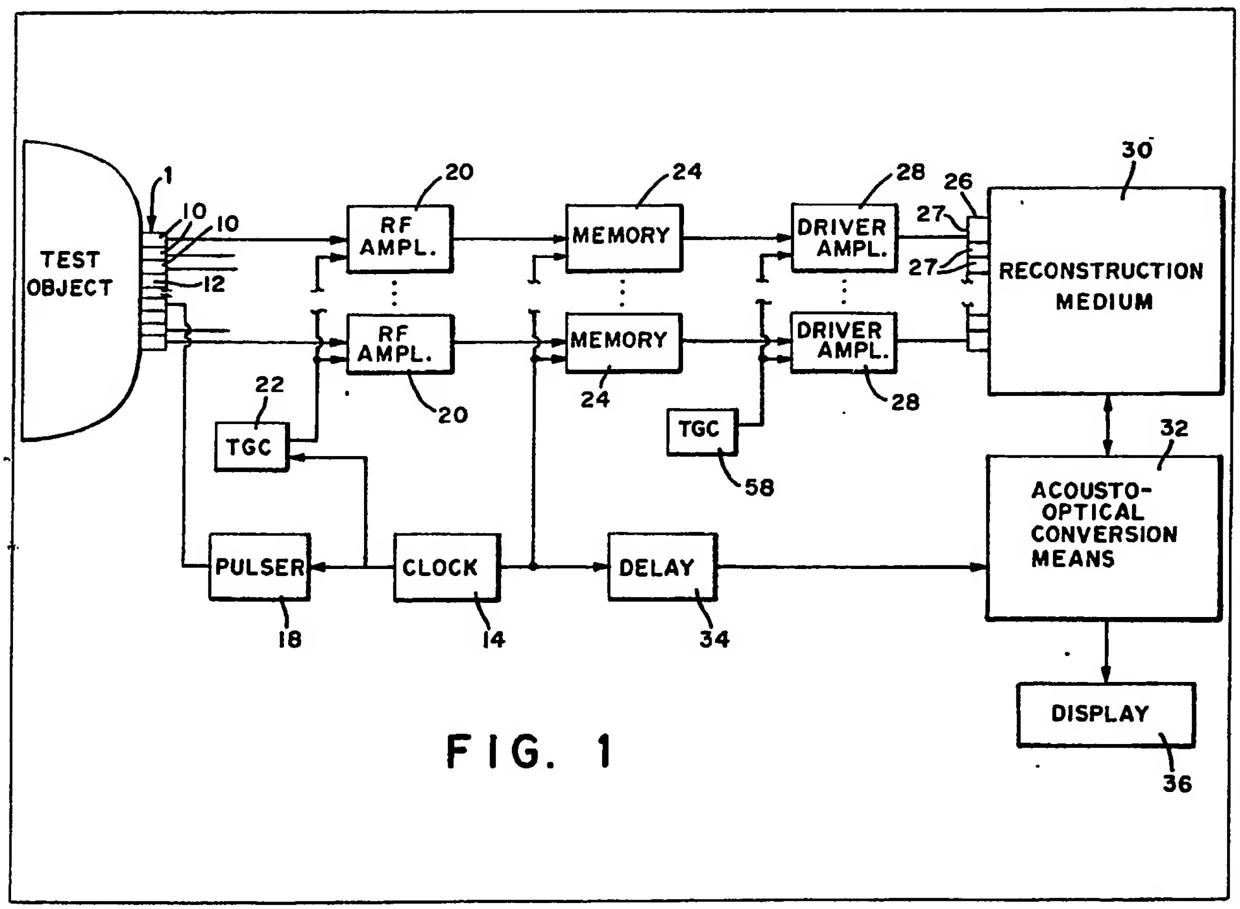

FIG. 1

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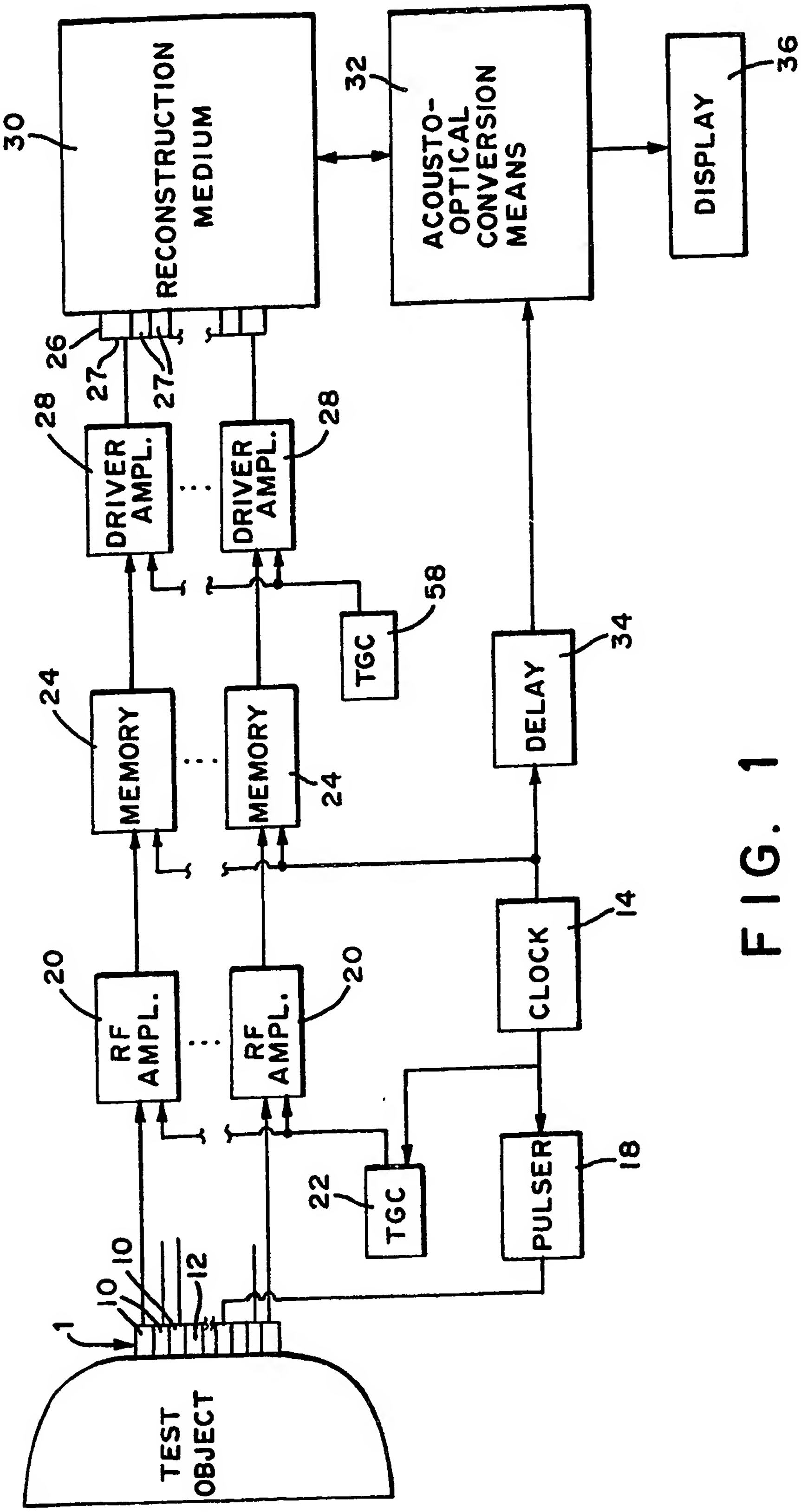
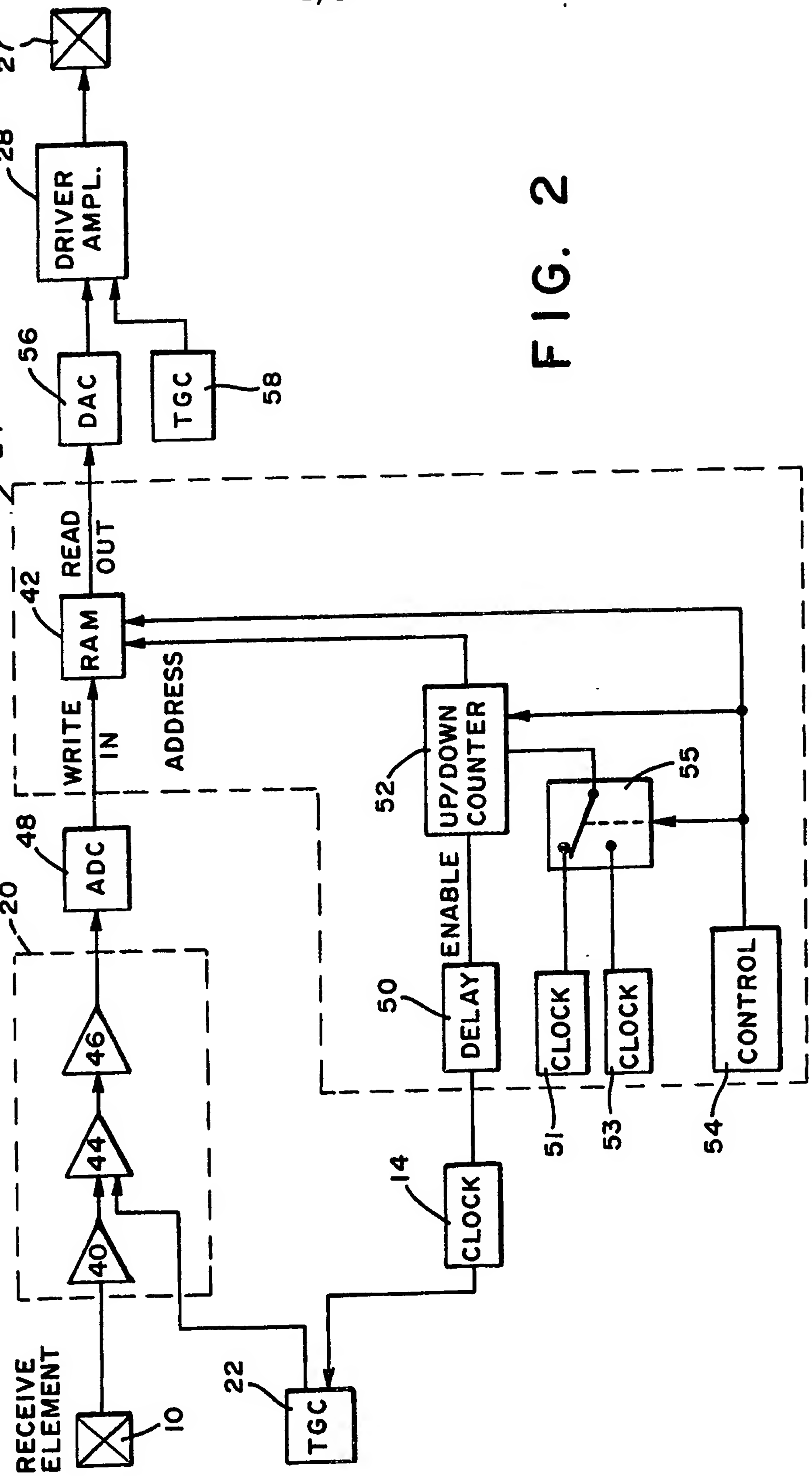


FIG. 1



RECEIVE ELEMENT
10
40
44
46
20
22
TGC
14
CLOCK
ADC
48
WRITE IN
ADDRESS
RAM
42
READ OUT
24
50
DELAY
ENABLE
52
UP/DOWN COUNTER
55
CLOCK
51
CLOCK
53
CONTROL
54
DAC
56
TGC
58
DRIVER AMPL.
28
27

FIG. 2

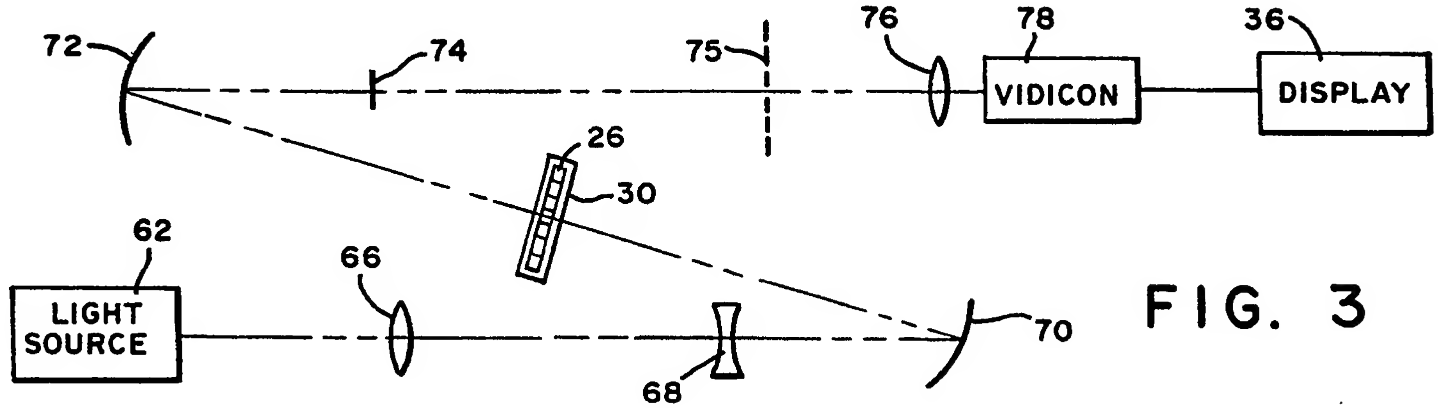


FIG. 3

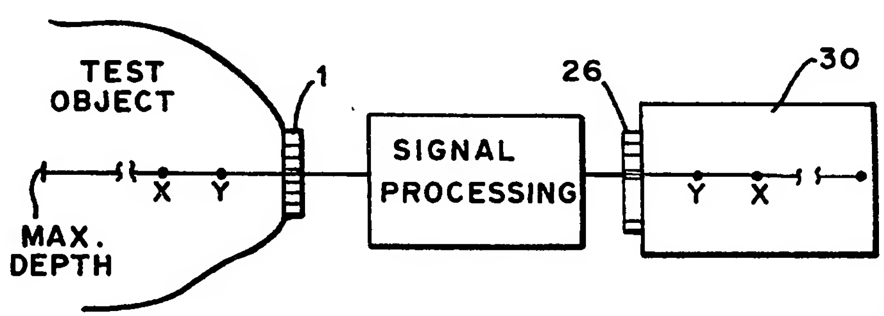


FIG. 5

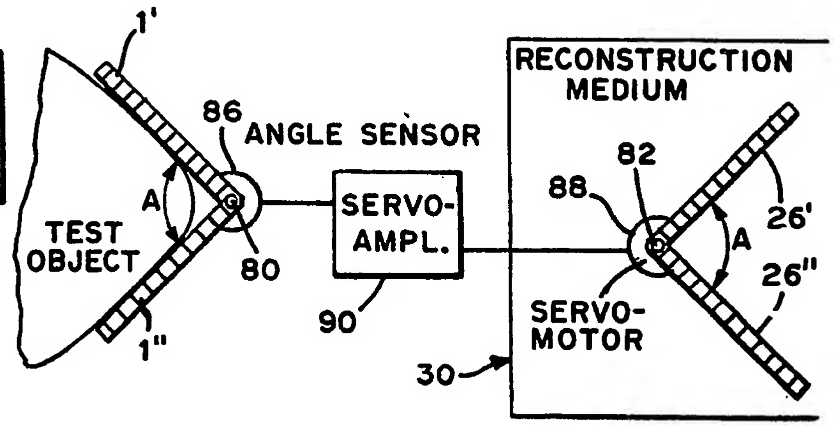


FIG. 6

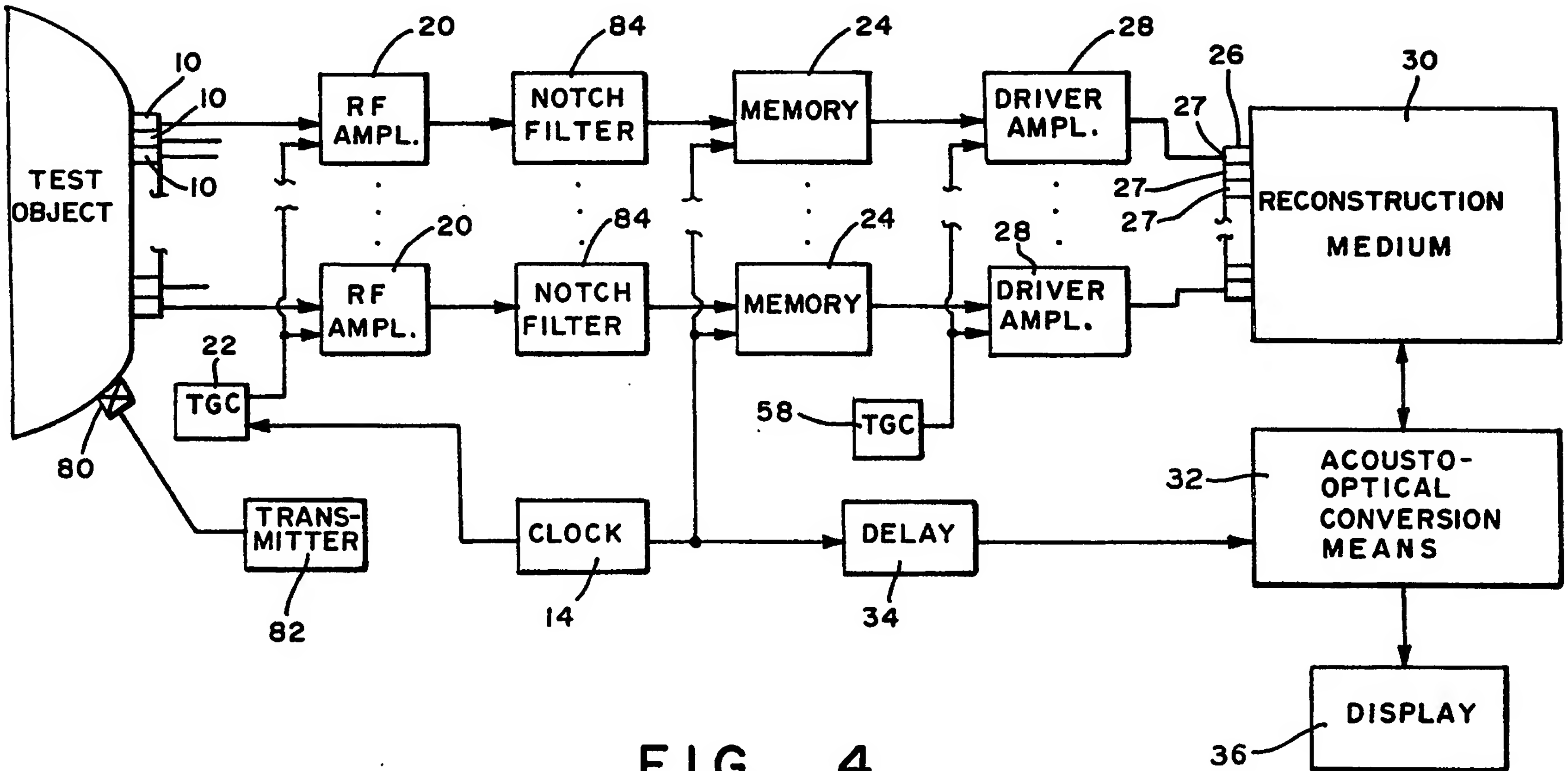

TEST OBJECT
10
10
10
10
80
TRANS-MITTER
82
22
TGC
20
RF AMPL.
20
RF AMPL.
84
NOTCH FILTER
84
NOTCH FILTER
CLOCK
14
24
MEMORY
24
MEMORY
58
TGC
DELAY
34
28
DRIVER AMPL.
28
DRIVER AMPL.
26
27
27
27
30
RECONSTRUCTION MEDIUM
32
ACOUSTO-OPTICAL CONVERSION MEANS
36
DISPLAY

FIG. 4

SPECIFICATION

Ultrasonic imaging system

The present invention broadly refers to real-time display ultrasonic echography apparatus and method. More particularly, the present invention concerns a real-time ultrasonic echography apparatus and method in which a visual image is constructed from an acoustic image formed in a reconstruction medium using acousto-optical techniques.

The present invention provides an ultrasonic imaging system comprising: transducer means adapted to be coupled to an object to be examined for transmitting ultrasonic energy into the object; a receive transducer array having a plurality of juxtaposed receive elements disposed for receiving echo signals responsive to said ultrasonic energy intercepting acoustic reflectors in the object and converting said echo signals into echo responsive electrical signals; memory means coupled to said receive transducer array for sequentially storing with respect to time data commensurate with said echo responsive electrical signals associated with each of said receive elements and for retrieving said stored data in time-reversed order of said sequentially storing; a reconstruction medium which conducts ultrasonic energy signals and in which an acoustic image may be formed; a reconstruction transducer array having a plurality of juxtaposed transmit elements coupled to said memory means and to said reconstruction medium for transmitting responsive to the retrieved time-reversed signals ultrasonic energy signals from said transmit elements into said reconstruction medium for forming a reconstructed acoustic image of the acoustic reflectors; acousto-optical conversion means coupled to said reconstruction medium for converting said reconstructed acoustic image into an optical image;
control means coupled to said memory means for controlling the rate of storing of said data and the rate of read-out of said data in time reversed order, and display means coupled to said acousto-optical conversion means for displaying said optical image.

The present invention also provides a method of producing an optical image in an ultrasonic imaging system comprising: transmitting ultrasonic energy into an object to be examined; receiving echo signals responsive to said ultrasonic energy intercepting an acoustic reflector in the object and converting said echo signals into echo responsive electrical signals; storing data commensurate with said echo responsive electrical signals in received sequential order; retrieving said stored data in time-reversed order; transmitting responsive to said retrieved time-reversed data ultrasonic energy signals into a reconstruction medium for forming a reconstructed acoustic image of the acoustic reflector, and converting said reconstructed acoustic image into an optical image.

It is possible, as will be described hereinafter, to obtain isochronous images, that is images in which the entire acoustic image appears simultaneously in the reconstruction medium and the reconstruction medium is pulsed by a light source to obtain a visual image of the acoustic field, or to derive anisochronous images in which the image forms at different depths in the reconstruction medium as a function of time and the reconstruction medium is scanned by a light source to obtain a visual image of the acoustic field.

The present arrangement, with minor modifications, is useful in both pulse-echo and Doppler imaging. Additionally, an M-mode presentation may be simultaneously displayed with the real-time image. The M-mode scan line can be derived from the same receive array and the same transmit pulses that are used to obtain the real-time image by using conventional phased array techniques to form an ultrasonic receive beam in the direction selected for M-mode imaging.

Due to the high scan frame rate achieved by the present arrangement, it is possible to substantially eliminate speckle patterns. Speckle patterns in imaging apparatus is described in detail in the article entitled "Acoustic Speckle: Theory and Experimental Analysis" by John G. Abbott and F.L. Thurstone, *Ultrasonic Imaging*, vol. 1, no. 4, October 1979, pp. 303–324, Academic Press, New york and London.

In the prior art, specifically in U.S. Patent No. 4,174,634 issued to J. Dory, dated November 20, 1979 and entitled "Echographic Device for the Real-Time Display of Internal Discontinuities of a Test Object", acoustic lens and mirror means are employed to create an acoustic image in a reconstruction medium. By the use of an acousto-optical imaging system the acoustic image in the reconstruction medium is converted into a visual representation. The prior art arrangement has several shortcomings particularly, the image size is reduced but the resolution is limited by the wavelength of the original ultrasound frequency transmitted and received. The length of the water path has the effect of reducing both the image resolution and sensitivity because acoustic energy is dispersed as the square of the path length.

In addition to the aforementioned patent, other prior art publications include U.S. Patent No. 4,006,627, issued to J. Bossaert, dated February 8, 1977 entitled "High-Speed Ultrasonic Echo-Tomographic Device." In this patent ultrasonic signals are transmitted into a reconstruction medium comprising crystalline material. In U.S. Patent No. 4,157,665, issued to E. Bridoux et al, dated June 12, 1979 entitled "Formation of Acoustical Images", received signals are

processed by a system comprising a high frequency oscillator so as to produce a beat frequency signal which has the effect of converting a diverging beam into one which converges to an image in a reconstruction medium.

In all of the above described prior art arrangements there is an absence of time-reversal of the echo responsive electrical signals. In the present invention the echo responsive electrical signals arising from echoes in the object under examination are processed and sequentially stored in a memory means associated with each transducer element of the receive array. The signals are retrieved from the memory means in time-reversed order, that is, the last signal sequentially stored in the memory is the first signal retrieved. The retrieved signals are further processed and finally provided to associated transducer elements of the reconstruction array. The reconstruction array, acoustically coupled to a reconstruction medium, transmits into the medium acoustic energy signals responsive to the time-reversed echo responsive electrical signals. Depending upon the reconstruction medium, Schlieren, Bragg, interferometry or other acousto-optical conversion techniques are used to construct the visual image. Optical imaging techniques are well known and described, for example, in the book *Biomedical Ultrasonics* by P.N.T. Wells 1977, Academic Press, at pages 98 to 106, in the article "A New Ultrasonic Focusing System for Materials Inspection" by P. D. Hanstead, J. Phys. D: Appl. Phys., vol. 7, 1974, pages 226 to 241, and in British Patent no. 1,364,254 of P. D. Hanstead, entitled "Improvements in Ultrasonic Inspection."

It is possible, using the present arrangement, to read out the stored data from the memory means at a higher rate than the data was written into the memory. Similarly, it will be apparent that the data can be read out at the same rate or at a slower rate than the write-in rate of the data.

In a modification of the present arrangement, it is possible to obtain Doppler images. In a still further modification color displays may be obtained.

The present invention will become more clearly apparent when the specification is read in conjunction with the accompanying drawings.

Figure 1 is a schematic electrical block diagram of a preferred embodiment of the invention;
Figure 2 is a schematic block diagram of a portion of the arrangement per Fig. 1;
Figure 3 is a schematic diagram of another portion of the arrangement per Fig. 1;
Figure 4 is a schematic electrical block diagram of another embodiment of the invention;
Figure 5 is a diagram of a portion of the embodiment per Fig. 1, and,
Figure 6 is a diagram showing a modification of a portion of the embodiments disclosed in Figs. 1 and 4.

Referring now to the figures, Fig. 1 shows a schematic electrical block diagram of a preferred embodiment of the invention for use in pulse echo echography. An array 1 of electroacoustic receive elements 10 is acoustically coupled to an object to be examined. At least one element 12 of the array is a transmit element or a transmit/receive element. While in the figure the transmit element 12 is medially disposed along the array, the element 12 may be disposed at either end of the array, at any intermediate location or even remote from the array 1. Preferably, the transmit element 12 is disposed at a position where the transmitted ultrasonic energy is not blocked by a non-transmissive element. For example, if the object to be examined is a human heart, the element 12 would be disposed at a position away from a rib or costal cartilage. In a typical embodiment the array 1, comprises from 32 to 100 elements 10.

A clock 14 provides trigger pulses to a pulser 18 at a frequency dependent on the speed of sound in the object and the maximum depth which is to be examined in the object. The trigger pulse repetition frequency is typically in the range between 100 Hz and 2 kHz and in the case of adult cardiology or abdominal echography the preferred frequency is approximately one kilohertz. The pulser 18, in turn, provides excitation pulses to the transmit element 12. The transmit element 12 converts the excitation pulses from pulser 18 to ultrasonic energy transmit pulses which are cyclically transmitted into the object to be examined, generally to insonify an entire plane of the object to be examined. Upon intercepting an acoustic discontinuity or a boundary in the object (also referred to as a reflector or a scatterer) a portion of the ultrasonic transmit pulse energy is scattered back toward the receive elements 10 as echo signals. The received echo signals are converted into echo responsive electrical signals by the receive elements 10.

The echo responsive electrical signals are provided to a respective radio frequency amplifier 20 associated with each receive element 10 of the array.

A first time gain compensation (TGC) circuit 22 provides a compensation signal to each radio frequency amplifier 20 for adjusting the gain of the amplifier 20 so that echo signals of the same magnitude arising from reflectors disposed at different depths in the test object are of the same amplitude at the output of the radio frequency amplifier 20. The construction of TGC circuits is well known in the art.

The output signal of each amplifier 20 is provided with respect to time to memory means 24 where each output signal is simultaneously written into the memory means 24 with respect to

time. Depending upon the specific memory means 24 employed, an analog-to-digital converter and/or a driver amplifier may be inserted in the circuit between the amplifier 20 and the memory means 24.

While in the drawings memory means 24 is illustrated as a discrete memory associated with each element 10, in actual construction there is usually one memory means with separate portions of the memory associated with each element for simultaneously storing and reading-out data associated with each respective element of the receive array.

When the signals from each receive element 10 of the array is stored in memory means 24 with respect to time the data are read out of the memory in time-reversed order in parallel for each element 10. That is, the last signal written into memory means 24 associated with each element 10 is the first signal read out and so forth. The signal data are written into the memory means 24 for a period of time required for an echo signal reflected from a reflector disposed at the maximum depth of the object under examination to reach the receive elements 10 and to be written into the memory means 24.

The read-out speed can be greater than, less than, or equal to the write-in speed. Depending upon the reconstruction medium and whether an isochronous or an anisochronous image is to be created, the read-out speed is adjusted as will be described below.

The data from echoes closest to the receive array are received, processed and stored in the memory means first. Data arising from discontinuities disposed at the furthest point of the object to be examined are received, processed and stored in the memory means last. In order to reconstruct the image in the reconstruction medium 30, the wave fronts and images arising from points furthest from the array must be transmitted into the reconstruction medium first. This concept is most apparent in the case of an isochronous imaging arrangement. In order to achieve an isochronous image, the last data stored in memory 24 must be the first data retrieved and transmitted into the reconstruction medium. This time-reversal concept is of greatest significance for the invention as will be explained in detail hereinafter.

In the case of anisochronous imaging, the time-reversal concept is equally important since a scatterer (or reflector) scatters the impinging ultrasonic energy in all directions. Portions of the scattered energy arrive at different elements 10 of the receive array at different instances of time by virtue of the different path lengths from the scatterer to the respective elements of the array 10. By applying time-reversed data signals to the elements of the reconstruction array 26, the retransmitted signals will follow paths in the reconstruction medium 30 which converge at the same locations with respect to the reconstruction array 26 as the locations of the scatterer with respect to the receive array 10. It is the desire to reconstruct the scatterers in the reconstruction medium 30 which necessitates the use of the time-reversal concept.

The time-reversed output from memory means 24 is fed to the elements 27 of the reconstruction array 26 via respective driver circuits 28. The elements 27 transmit acoustic energy signals into a reconstruction medium 30 responsive to the applied time-reversed signals. A second TGC circuit 58 provides compensation signals to the respective driver amplifier circuits 28 to provide compensation to the time-reversed output signals for the energy dispersion manifest in the reconstruction medium 30 so that reflectors of equivalent magnitude at different distances in the reconstruction medium 30 are represented by equivalent pressure amplitudes.

Depending upon the specific memory means employed, a digital-to-analog converter may be inserted in the circuit between the memory means 24 and the driver amplifier 28.

An acousto-optical conversion means 32 is associated with the reconstruction medium 30 to form an optical image of the accoustic energy patterns transmitted into the medium 30 by the elements of the array 26.

If the reconstruction medium is an optically transparent medium, for example water or gas in a tank, then a Schlieren system may be used. If the reconstruction medium is an optically opaque medium, such as a solid comprising a piezoelectric crystal or a crystalline metal, a Sokolov tube, a Bragg refraction apparatus or an interferometer may be used. The conversion of the acoustic energy pattern to an optical image is well known and is described in the prior art patents and in the book *Biomedical Ultrasonics* supra.

Whether the reconstructed image is isochronous requiring a single light pulse, for instance from a pulsed laser or a flash lamp, in a Shclieren system to form the image, or whether the image is anisochronous and the reconstruction medium is scanned by a light source, the acousto-optical conversion means is synchronized to the trigger pulse by means of a delayed clock signal from delay 34. The optical image from the acousto-optical conversion means 32 is provided to a display 36. The display 36 may be a video image from a vidicon tube or a screen for viewing directly the image from the acousto-optical conversion means 32.

The reconstruction medium 30 can be a solid, liquid or gas. A gas, such as air, provides the advantage that the size of the image and the acousto-optical means can be reduced by a factor of three compared to that of water but, has the related disadvantage that the reconstruction array 26 must be made much smaller dimensionally than the receive array 1.

Having generally described a preferred embodiment, reference is now made to Fig. 2 in which

a detailed schematic block diagram of one channel of the foregoing arrangement is shown. It will be understood that each of the elements 10 of array 1 has an associated channel.

The received echo signals are converted by a respective receive element 10 of array to echo responsive electrical signals which are fed to a preamplifier 40. The output of preamplifier 40 is provided to an amplifier 44 which amplifies the output signal from preamplifier 40 and provides distance compensation for the depth dependent attenuation of the echo signal by virtue of a time gain compensation signal from TGC 22. The output signal from amplifier 44 is fed to a driver circuit 46.

Since in the embodiment in Fig. 2 the memory means 24 is a random access memory (RAM) device, an analog-to-digital converter (ADC) 48 is connected in the circuit between the driver 46 and the memory means 24. It will be understood that for other memory devices, such as analog devices, for instance a charge coupled device (CCD), the ADC 48 is unnecessary.

The ADC 48 sequentially provides digital data to the memory means 24 corresponding to the echo signals received by the respective element 10. Depending upon the desired maximum examination depth in the test object, the length of time that signals are received, processed and stored in memory 24 means is determined. It will be understood that the storage process occurs simultaneously for each element 10 of the receive array.

Clock 14, in addition to providing trigger pulses to pulser 18 and synchronization pulses to delay 34 for synchronizing the acousto-optical conversion means 32, also provides a pulse to a second delay means 40. The delay means 50 is adjusted to cause an up/down counter 52 to commence counting at a predetermined time after a trigger pulse is provided to transmit element 12. The up/down counter 52 performs as an address sequencer for the RAM 24.

The rate of counting by the up/down counter is determined by whether clock 51 or clock 53 is coupled to the up/down counter 51 via switch means 55. The direction of counting, the rate of counting and whether the RAM is writing-in data or reading-out data are all determined by a control unit 54.

Clock 51 provides pulses at a high frequency, typically at a frequency in the range between 10 MHz and 100 MHz. As the up/down counter 48 counts in a first direction, the digital data output at ADC 48 is stored in RAM 24 at an address location determined by the output count from counter 52. After all the data are stored in memory means 24, a signal from control unit 54 causes clock 53 to be coupled to the counter 52, causing the RAM 24 to read out data and the up/down counter 52 to count in the opposite direction.

In a preferred embodiment, the frequency of clock 53 (the read-out rate) is adjusted for causing the data to be read out of the memory means 24 and the acoustic energy to be transmitted by the associated element 27 into reconstruction medium 30 a rate suitable for forming an isochronous image. Adjustment of the clock 53 frequency to any other value will result in the formation of an anisochronous image in the reconstruction medium 30.

In order to suitably adjust the read-out rate, first let it be assumed that the reconstruction medium 30 has the same acoustic velocity as the object being examined. In that case, the read out rate will be twice that of the write-in rate. Referring to Fig. 5, the time to receive an echo from point in the test object and to reconstruct the same point in reconstruction medium 30 is:

$$\frac{T - 2d_X/Vo}{R} + d_X/V_r$$

where T is the time to record data from the maximum depth to be examined, d_X is the distance from the center of the array 1 to the point X in the object and also the distance from the center of the array 26 to point X in the reconstruction medium; Vo is the acoustic velocity in the test object; V_r is the acoustic velocity in the reconstruction medium, and R is the read-out rate, whereas the time to reconstruct point Y in the reconstruction medium 30 is:

$$\frac{T - 2d_Y/Vo}{R} + d_Y/V_r$$

where d_Y is the distance from the center of the array 1 to the point Y in the object to be examined and also the distance from the center of the array 26 to point Y in the reconstruction medium.

This analysis is simplified to the extent of one transmit/receive element, one reconstruction element, and that points X and Y lie along the common axis being reconstructed. It can be shown that similar results are obtained with off-axis points and muliple element arrays. The simplified analysis is presented for the purpose of describing the general principle involved.

The time intervals

$$\frac{T - 2d_X/Vo}{R}$$

and

$$\frac{T - 2d_Y/Vo}{R}$$

are the time intervals required to retrieve the stored data for points X and Y respectively from the memory means 24. The quotients d_X/V_r and d_Y/V_r are the time intervals for the points X and Y to be formed in the reconstruction medium.

In order to achieve an isochronous image in the reconstruction medium 30, all points must be formed at the same instant of time. Therefore, the following relationship must exist for an isochronous image:

$$\frac{T - 2d_X/Vo}{R} + d_X/V_r = \frac{T - 2d_Y/Vo}{R} + d_Y/V_r$$

Initially, let it be assumed that the acoustic velocity in the object (Vo) and the acoustic velocity of the reconstruction medium (V_r) are equal, i.e. $Vo = V_r$, and further that the dimensions of the test object and that of the reconstruction medium are equal, then solving the above equation for any points X and Y requires that R must be equal to two. Therefore, the rate of read-out of data from memory means 24 into a reconstruction medium 30 having the same acoustic velocity and dimensions as the object under examination is twice the write-in rate.

With regard to the reconstruction of points disposed off-axis, it will be understood that the path length from the centrally disposed transmit element 12 to the reflector and back to the receive element differs from the path length in the reconstruction medium from the reconstruction array element to the imaged reflector. Assuming that the acoustic velocity of the object and that of the reconstruction medium are substantially equal and that the time-reversed data is read-out at twice the write-in rate, then be separating the juxtaposed elements 27 in the reconstruction array from each other by one-half the distance between juxtaposed elements 10 of the receive array distortion due to the different acoustic path lengths in the respective media can be reduced in the far-field, i.e. for points located far from the reconstruction array 26. In the near-field, i.e. at points closer to the reconstruction array 26, there is distortion. This distortion arises from the desire to achieve isochronous images. The spacing between juxtaposed elements may be empirically varied from one-half spacing slightly to effect a compromise between the near field and the far field image distortion.

In the case where the object and the reconstruction medium have the same acoustic velocity, and when the read-out rate is made equal to the write-in rate, the reconstructed image does not exhibit the described near-field distortion. The improved near-field resolution is exchanged for the formation of an anisochronous image instead of an isochronous image.

In the case of either isochronous or anisochronous images use of a reconstruction medium with an acoustic velocity different from that of the test object can be used to change the size of the reconstructed image. If the read-out rate is constant and all the dimensions of the reconstruction array are changed in proportion to the wavelength of the ultrasound in the reconstruction medium then the ratio of the size of the image in the reconstruction medium to that in the test object will be the same as the ratio V_r/V_o.

Referring again to Fig. 2, the data read out of RAM 42 are provided to a digital-to-analog converter 56 (if a RAM is used for the memory means; however, the DAC is unnecessary if an analog memory device, such as CCD memory device, is used). The second TGC 58 controls the gain of driver amplifier circuit 28 to compensate the output signal from DAC 56 for the dispersion of energy in the reconstruction medium 30 as described above.

While the above description refers to a RAM memory device, a CCD device which sequentially stores analog values and provides output analog signals in time reversed order may also be used. That is, the last signal stored is the first signal retrieved. Magnetic storage means or acousto-optical means, such as acoustical delay lines and a laser read-out, may be substituted for the RAM memory means. The modifications required in the embodiment per Fig. 1 to use equivalent memory means, for example the ellimination of clocking in the data when using an analog memory means, will be apparent to those skilled in the art.

The acousto-optical conversion of the reconstructed acoustic images may be by any of the known methods. In the preferred embodiment in which the read-out rate is adjusted for forming

an isochronous image as described above, a pulsed laser Schlieren arrangement is the preferred acousto-optical conversion means 32. A scanned laser Schlieren arrangement may be used for anisochronous images. Of course, Bragg diffraction, interferometry or cross-polarized filters may also be used depending upon the reconstruction medium. Each of these techniques is known in the art, see for example, the patents cited above, the book *Biomedical Ultrasonics*, or the Hanstead article supra.

Fig. 3 shows one method of using a Schlieren device to perform the acousto-optical conversion. A laser or pulsed light source 62 provides a pulse of light which passes through a converging lens 66 and then to a diverging lens 68 and to a concave mirror 70. The parallel beam of light from mirror 70 passes through the reconstruction medium 30 in a direction generally perpendicular to the direction of the acoustic energy transmitted into the medium 30 from array 26.

The light beam after passing through the optically transparent reconstruction medium 30 is reflected by another concave mirror 72 and brought to a focus at plane 74.

Light which is diffracted by the acoustic patterns in the reconstruction medium 30 travels different distances in traversing the remainder of the system, that is, past an obscurer at plane 74 and lens 76 to a vidicon 78. The output of the vidicon 78 is provided to the display 36. The diffracted and non-diffracted light interfere with each other to produce an image of the acoustic pattern at the plane 75. It is possible by means of disposing various filters at the Fourier plane 74 to modify the image.

Although the lenses are shown as simple single elements, all or any of them may in practice by multi-element lenses to aid precision in the direction and focussing of the light rays to form the final image.

The physical size of the Schlieren arrangement may be made more compact by using mirrors for folding the light path.

It will be apparent that if the reconstruction medium is optically opaque, alternative acoustic-optical conversion techniques may be used as indicated hereinabove.

The arrangement per Fig. 3 is advantageous for pulsed laser operation. Specifically, when isochronous images are formed in the reconstruction medium 30, the timing of the light pulse is synchronized by means of delay 34 to provide a pulse of light for illuminating the medium 30 at the instant the acoustic image is formed.

Alternatively, if anisochronous images are created, images are first formed at the end of the medium 30 furthest from the array 26 and then are formed at locations closer to the array 26. A known scanning means, such as that described in the Dory patent supra, may be used to scan the medium with the laser in synchronism with the image formation. The scanning is usually in the form of circles having smaller radii as the reconstruction medium is scanned closer to the elements 27. The light beam is optically, electrically or mechanically controlled to scan the reconstruction medium in synchronism with the location at with the image is being formed in the reconstruction medium (see Dory, supra).

In a still further variation, due to the large quantity of images formed per second (equal to the repetition rate of the trigger pulses from clock 14), it is possible to have the laser illuminate selected portions or sectors of the reconstruction medium with each laser pulse rather than illuminating the entire reconstruction medium with a single laser pulse.

As is the case with a pulsed laser, it is possible to scan the reconstruction medium in narrow sectors rather than by means of line scans.

In a further variation, the transmitted ultrasonic signal can originate from several transmit or transmit/receive elements disposed at different locations either along the array or remote therefrom. The purpose of multiple transmit signal sources is to change the speckle pattern in the visual image from frame-to-frame. Since the frame rate is high, the eye will average many frames for each percieved images. As a result the changing speckle pattern will be averaged out while the unchanging pattern arising from reflectors in the object is enhanced.

The use of ultrasonic signals originating from multiple sources does not affect the signal processing of the echo responsive electrical signals, especially with regard to time-reversal of the stored data.

The speckle pattern can be minimized by changing the position of the transmitting element during subsequent pulses or by changing the frequency of the transmitted pulses. Changing the frequency is simpler because changing the position of the transmit element is in effect a change of the reconstruction origin with the consequent change in the laser sweep pattern (anisochronous) or switching to atlernative elements of the retransmit array (isochronous).

It will be apparent to those skilled in the art that the transducer array 10 may comprise transmit/receive elements instead of only receive elements and a single transmit element. Furthermore, it is possible to excite the transmit elements in a phased array manner to change the focal zone and/or the directivity of the transmitted ultrasonic beam. It is also possible to transmit a search beam for examining the entire image plane or to examine a narrower section which can be steered or scanned to examine the entire image plane with several search pulses.

The receive array 10 can be a single linear array, several array segments or a two dimensional array. Moreover, the receive array may comprise several rows of elements to facilitate dynamic focusing in the direction perpendicular to the plane of scan.

Fig. 4 shows a modification of the embodiment per Fig. 1 useful for Doppler measurements. The ultrasonic energy is transmitted into the test object via transmit transducer 80 disposed remote from receive array elements 10. A continuous wave transmitter 82 excites transducer element 80 for transmitting continuous wave (CW) narrow bandwidth ultrasonic signals into the test object. Alternatively, the narrow bandwidth excitation may result from long-duration pulses rather than CW signals. The echo signals received by the elements 10 are converted into echo responsive electrical signals and provided to RF amplifiers 20. The gain of a respective amplifier 20 is adjusted via a compensation signal from TGC 22 to provide that signals arising from reflectors of the same magnitude disposed at different depths in the object are of the same amplitude at the output of amplifier 20. The output signals from aplifiers 20 are fed to associated notch filters 84. The notch filter 84 filters the Doppler frequency shift signals from the time gain compensated echo responsive electrical signals. The filtered signal at the output of notch filter 84 is stored in memory means 24 and relaunched by reconstruction array 26 in the same manner as the pulse-echo signals described above. The reconstruction medium will image only the Doppler signal instead of the pulse echo signals. Otherwise, the modified embodiment performs substantially as has been described above. A significant deviation from the pulse-echo technique arises from the fact that the transmit transducer 80 transmits continuous wave (CW) narrow bandwidth ultrasonic energy into the object being examined. Since CW ultrasonic energy is used, the memory means 24 can be programmed to commence storage at any time and continue storing for a time interval required for signals to be received from the maximum depth to be received, processed and stored. After data storage is completed the stored data are read-out in time-reversed sequence as described above.

In a variation of the described arrangement it is possible to write-in data for a much shorter time such as the period of the center frequency of the ultrasound, and read-out the data repetitively in a time-reversed manner until wavefronts have propogated to the maximum depth of the reconstruction medium.

In a modification of the embodiment per Fig. 4, the Fourier transform of the data signals is provided, for example from a fast Fourier transform (FFT) device, and stored in the memory means. Storage of the Fourier transform will result in reduced data storage and in the elimination of the notch filters 84 if the spectral components close to the center frequency of the transmitted ultrasound are disregarded. After storing the Fourier transform data without the center frequency spectrum data, the time reversed waveforms are easily synthesized from the stored spectra data.

As is well known when using Doppler techniques, it is essential to align the transmit and receive transducers so that the path length associated with a moving reflector undergoes substantial variations as a result of the reflector's movement. In order to achieve highest sensitivity of echo signals arising from flowing blood cells regardless of the flow direction, it is advantageous to use multiple transmitting transducers disposed remote from the receive array. The multiple transmit transducers may be activated either sequentially or simultaneously. If the transducers are properly disposed in a known manner the velocity vector in any direction will result in a substantial and readily detectable Doppler shift in the echo responsive electrical signal.

In both the pulse-echo and Doppler arrangements, the receive array may have any shape from linear to curvilinear. The reconstruction array must have a shape related to that of the receive array such that relaunched wavefronts reconstruct the pattern of scatterers. It is even possible, as shown in Fig. 6 to have the shape of the receive array adjustable to conform to the contour of the object being examined. In Fig. 6, the receive array comprises, for example, two linear segments comprising 1′ and 1″ joined at a hinge 80. Likewise, the reconstruction array comprises two linear segments 26′ and 26″ joined at hinge 82. Electrical means for maintaining the same spatial relationship between the array segments, such as a servomechanism which includes an angle sensor 86 for providing a feedback signal indicative of the angle between the array segments 1′ and 1″ to a servoamplifier 90 may be used. The output signal from servoamplifier 90 is provided to a servomotor 88 for adjusting the angle between segments 26′ and 26″ which are coupled to the servomotor 88. The segments are coupled to the servomechanism system so that the angles A in both the receive array and the reconstruction array are identical. In the present embodiment, assuming the reconstruction medium 30 is a tank filled with water, the reconstruction array is disposed within the tank of water. then from the reflector to an element 10 of the receive array is different from the distance traveled by the reconstructed signal from an element of the reconstruction array 26 to the reflector imaged in the reconstruction medium 30. This distortion is more evident in the near-field. In the far-field the difference in path lengths becomes negligible.

In an attempt to compensate for this path length difference, it is possible to contour the

reconstruction array elements 27 to transmit elliptic wavefronts instead of spherical wavefronts. The foci of the elliptic wavefronts to simulate the path length from the center of the array to the reflector and back to a receive element are the position of the receive element and the center of the reconstruction medium. The result is improved resolution in the near-field. In the far-field the ellipses will degenerate into circles and not provide significant image resolution improvement.

In a further modification of the arrangement, the remote transmit transducer may be oriented so that the transmitted plane wave is travelling in a direction perpendicular to the image plane. This modification allows insonification of the entire image plane at the same instant of time. It will be apparent to one skilled in the art that under this condition the time-reversed relaunching of the echo responsive electrical signal data into a reconstruction medium having the same acoustic velocity as the object under examination yields isochronous images without resorting to an increased data read-out rate. In this case the reconstruction array should have the same dimensions as the receive array.

It is also possible, especially using Doppler techniques for displaying blood flow, to provide a color presentation. Some simple techniques for creating a color display are the use of a color overlay over a black and white echo image or the use of three transmit pulse frequencies and providing images from a first frequency to one gun of a color video monitor, the second frequency image to another gun of the monitor and a third frequency image to the third gun of the monitor. For a detailed discussion of a method of providing such a color display see U.S. Patent No. 3,156,110 issued to M.E. Clynes, dated November 10, 1964, entitled "Ultrasonic Detection and Visualization of Internal Structure".

While there has been described and illustrated a preferred embodiment of a pulse-echo imaging arrangement using time-reversal memory means and a Doppler imaging arrangement using time reversal memory means and several variations and modifications thereof, it will be apparent to those skilled in the art that further and still other variations and modifications may be made without deviating from the broad principle of the invention which shall be limited solely by the scope of the appended claims.

What is claimed is:

CLAIMS

1. An ultrasonic imaging system comprising:

transducer means adapted to be coupled to an object to be examined for transmitting ultrasonic energy into the object;

a receive transducer array having a plurality of juxtaposed receive elements disposed for receiving echo signals responsive to said ultrasonic energy intercepting acoustic reflectors in the object and converting said echo signals into echo responsive electrical signals;

memory means coupled to said receive transducer array for sequentially storing with respect to time data commensurate with said echo responsive electrical signals associated with each of said receive elements and for retrieving said stored data in time-reversed order of said sequentially storing;

a reconstruction medium which conducts ultrasonic energy signals and in which an acoustic image may be formed;

a reconstruction transducer array having a plurality of juxtaposed transmit elements coupled to said memory means and to said reconstruction medium for transmitting responsive to the retrieved time-reversed signals ultrasonic energy signals from said transmit elements into said reconstruction medium for forming a reconstructed acoustic image of the acoustic reflectors;

acousto-optical conversion means coupled to said reconstruction medium for converting said reconstructed acoustic image into an optical image;

control means coupled to said memory means for controlling the rate of storing of said data and the rate of read-out of said data in time-reversed order, and

display means coupled to said acousto-optical conversion means for displaying said optical image.

2. An ultrasonic imaging system as set forth in claim 1 in which said transducer means is adapted to transmit ultrasonic energy into the object by transmitting ultrasonic transmit pulses into the object.

3. An ultrasonic imaging system as set forth in claim 1, in which said transducer means is adapted to transmit ultrasonic energy into the object by transmitting a continuous wave ultrasonic signal into the object, and notch filter means are coupled to said receive transducer means for receiving said echo responsive electrical signals and forming an output signal indicative of the Doppler frequency shift of said echo responsive electrical signals and providing said output signal to said memory means.

4. An ultrasonic imaging system as set forth in claim 1, in which said transducer means is adapted to transmit ultrasonic energy into the object by transmitting a long-duration narrow bandwidth pulse ultrasonic signal into the object, and notch filter means are coupled to said receive transducer means for receiving said echo responsive electrical signals and forming an

output signal indicative of the Doppler frequency shift of said echo responsive electrical signals and providing said output signal to said memory means.

5. A method of producing an optical image in an ultrasonic system comprising: transmitting ultrasonic energy into an object to be examined; receiving echo signals responsive to said ultrasonic energy intercepting an acoustic reflector in the object and converting said echo signals into echo responsive electrical signals; storing data commensurate with said echo responsive electrical signals in received sequential order; retrieving said stored data in time-reversed order; transmitting responsive to said retrieved time reversed data ultrasonic energy signals into a reconstruction medium for forming a reconstructed acoustic image of the acoustic reflector, and converting said reconstructed acoustic image into an optical image.

6. A method of producing an optical image as set forth in claim 5 including transmitting ultrasonic energy in the form of transmit pulses.

7. A method of producing an optical image as set forth in claim 5, including transmitting ultrasonic energy in the form of continuous wave ultrasonic signals.

8. A method of producing an optical image as set forth in claim 5 including transmitting ultrasonic energy in the form of long-duration narrow bandwidth pulse ultrasonic signals.

9. A method of producing an optical image as set forth in claims 5 or 6 including providing a signal indicative of the Doppler frequency shift of said echo responsive electrical signal for storing in received sequential order.

10. An ultrasonic imaging system as claimed in claim 1 substantially as hereinbefore described with reference to Fig. 1 to 3 and 5 or Fig. 4 or Fig. 6.

11. A method of producing an optical image in an ultrasonic imaging system as claimed in claim 5 substantially as hereinbefore described.

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